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Diffusion coefficients of supercritical CO_2 in oil-saturated cores under low permeability reservoir conditions

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ABSTRACT

CO_2 diffusion in oil-saturated porous media with low permeability is of great importance for the project design, risk assessment, and performance forecast of carbon capture and storage (CCS) or enhanced oil recovery (EOR). This paper developed a method to determine CO_2 diffusion in oil-saturated cores under low permeability reservoir conditions. Core, crude oil and experimental parameters were taken from the representative low permeability reservoir. In the solution of the mathematical model, oil saturation was introduced in to diffusion equation, an oil-phase swelling caused by gas dissolution was considered, but a water-phase swelling was not, which is in agreement with the actual diffusion situation. The error caused by the state equation of carbon dioxide was eliminated, improving the calculation accuracy of the diffusion coefficient. The effects of pressure (6.490–29.940 MPa), temperature (70–150 °C), oil saturation (0–63.58%) and permeability (8.62–985.06 mD) on the diffusion coefficient of supercritical CO_2 in low-permeability reservoirs were studied. The order of the diffusion coefficient is from 10^{-10} to 10^{-9} m^2/s. The results show that with an increase in pressure and temperature, the CO_2 diffusion coefficient in the porous media saturated with oil firstly increases significantly and then the rate of increase gradually slowed down. The CO_2 diffusion coefficient increases greatly with the oil saturation in porous media. The CO_2 diffusion coefficient first increases greatly with permeability, and when the permeability of the core is greater than approximately 100 mD, it remains almost stable. The experimental results can provide theoretical support for CO_2 transport in porous media.

1. Introduction

1.1. Carbon capture, utilization and storage

Global warming caused by the excessive emission of greenhouse gases has become one of the most significant environmental problems. Flue gas from fossil fuel power plants is the largest long-term carbon dioxide emission source, which accounts for 30% of the total emissions. Carbon dioxide capture from power plant flue gas and geological storage is one of the potential ways of reducing greenhouse gas emissions to address global climate change [1–5]. Carbon capture and storage (CCS) has been widely regarded as a potential, alternative solution for the reduction of carbon dioxide in the atmosphere to mitigate climate warming [6–9]. However, the problem for CCS is that the profit is very small and that it cannot make up for the high cost. CO_2 enhanced oil recovery can not only achieve the reduction in carbon dioxide emissions but also improve the crude oil recovery of reservoirs; this process has been widely used in oil field development. CO_2 enhanced oil recovery possesses the most potential for carbon capture, utilization and storage (CCUS) [10–15].

1.2. Carbon dioxide diffusion in porous media

In the process of oil displacement by carbon dioxide, the diffusion of the injected carbon dioxide in porous media saturated with crude oil is particularly important. Therefore, determining the carbon dioxide diffusion coefficient in the porous media saturated with crude oil is important for the development of carbon dioxide flooding technology [16–20].

Many researchers have conducted the experiments on gas diffusion coefficients in bulk liquids since the 1930s using a PVT cell. The PVT method has been successfully used to measure the diffusion coefficient of gases in liquids under different pressures [21–25]. The dissolution of these gases into the liquids decreases the liquid density, which will not cause natural convection. However, the PVT method cannot be applied to measure CO_2 diffusion in most liquids with natural convection [26–29].

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Grogan et al. used a glass capillary instead of a PVT cell to measure the diffusion coefficient of CO_2 in light oil under high pressures [22]. To reduce the natural convection induced by the density decrease, the glass capillary was positioned horizontally. A CO_2 gas slug was injected into the middle of a capillary that was filled with oil. Although this method can be used to determine the diffusion coefficient of CO_2 in the liquid phase, it is difficult to be applied to the measurement of the diffusion coefficient in liquid-saturated porous media.

Renner proposed an experimental method using liquid saturated Berea cores to test the effective diffusion coefficient of CO_2 in porous media [17]. Glass fiber and epoxy resins were used for sealing one end face and the side surface of the Berea core in his measurement, so gas could only diffuse from one end face of the core. He found that the measured diffusion coefficient was much greater when the core was vertically placed than when the core was located horizontally due to the natural convection caused by the changes in density of the oil phase in the porous media.

Krooss developed an experimental method for measuring the effective diffusion coefficient of hydrocarbon gases in sedimentary rocks saturated with water at atmospheric pressure and at different temperatures [30,31]. A rock layer with a thickness of 3.10 mm that was cut from a rock plug was used as the porous media in their experiments. The authors noted that great care should be taken during the preparation and installation of the core samples, particularly for weakly consolidated rocks. They also suggested that the experimental apparatus was not appropriate for obtaining measurements under high pressures.

Li and Dong suggested an experimental method and mathematical model for measuring the diffusion coefficient of a gas in porous media saturated with oil. They used Berea cores saturated with water or crude oil as porous media in their experiments. Two end faces of the core were sealed for the physical model, and the gas could only diffuse from the radial direction through the core, which provided a greater diffusion area. The authors confirmed that the pressure decay was less sensitive to the environment [19,20,32].

1.3. Carbon dioxide capture and utilization in the Shengli Oilfield

The Shengli Oilfield of Sinopec in China has a coal-fired power plant (Shengli Power Plant), with the capacity of 1040 MW, and annual carbon dioxide emissions of 570×10^4 t. The Shengli Power Plant has built a carbon dioxide capture system with a capacity of 100t/d. At the same time, the Shengli Oilfield has low permeability reservoirs with crude oil reserves of approximately 3×10^8 t, which is suitable for carbon dioxide flooding. San 121 Block in Shengli Oilfield is located in the Fanjia nose structure zone of the Jiyang sag with a reservoir depth from 2695.1 m to 2711.2 m. The initial reservoir formation pressure is 31.1 MPa, and formation temperature is 130.2 °C. The reservoir porosity is 11.6–16.4%, and permeability is from 1.7 mD to 29.2 mD. The reservoir is with low porosity and low permeability.

1.4. Purpose of this paper

The CO_2 diffusion coefficient is an important input parameter for the large-scale modeling and stimulating of CCS or CO_2-EOR. However, few studies of the CO_2 diffusion coefficient in low permeability reservoirs are available, and we do not have sufficient information about the effects of temperature, pressure, oil saturation and permeability on the CO_2 diffusion.

In this study, a method to determine CO_2 diffusion in oil-saturated cores under low permeability reservoir conditions was developed. Through physical simulation experiments for the diffusion of carbon dioxide, the effects of temperature, pressure, oil saturation and permeability on the diffusion of CO_2 were investigated. Compared with the literatures related to the CO_2 diffusion coefficients in porous media [17,19,22,30,32], this paper presents three improvements. First, the core, crude oil and experimental parameters were taken from the representative low permeability reservoir from China, which has an important guiding significance for carbon dioxide storage and flooding. The experimental parameters are great enough to stimulate the actual low permeability reservoir. Second, the practical core of low permeability has a high irreducible water saturation, which is as high as 30–50%. In the mathematical model solution, oil saturation was introduced in to diffusion equation, and the effect of oil saturation on diffusion coefficient was considered. The oil-phase swelling caused by gas dissolution was considered and water-phase swelling was not, which is in agreement with the actual diffusion situation. Third, the corresponding physical parameters for carbon dioxide are from the database of the National Institute of Standards and Technology (NIST), eliminating the error caused by the state equation of carbon dioxide. The objective of this study

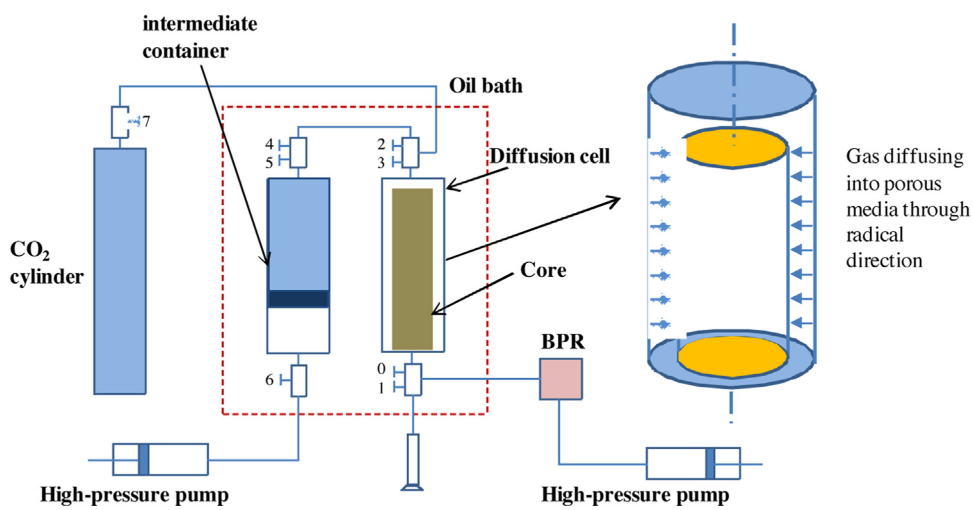

Fig. 1. Experimental apparatus.